March 17, 1999

Response to Reviewers' Comments Regarding Air Quality Effects of MTBE (Executive Summary and Volume III) University of California Report (UC Report) on the Effects of MTBE, performed under S.B. 521

Catherine P. Koshland, Donald Lucas, Robert F. Sawyer, Pamela M. Franklin
University of California, Berkeley

As part of the comprehensive evaluation of the gasoline oxygenate methyl tertiary-butyl ether (MTBE) performed by the University of California under the authority of S.B. 521, we conducted an evaluation of automotive MTBE combustion byproducts (Volume III – Air Quality and Ecological Effects). In order to accomplish this objective, we evaluated peer reviewed literature studies, analyzed an extensive database of vehicle dynamometer emissions, and performed our own laboratory experiments. We compared reformulated fuel with MTBE to non-oxygenated reformulated gasoline, and concluded that there is no significant additional air quality benefit to the use of MTBE in reformulated gasoline relative to non-oxygenated California Phase 2 Reformulated Gasoline (CaRFG2) formulations. The mandate for our study was to evaluate the automotive combustion byproducts of MTBE in the context of California's reformulated gasoline. Our evaluation and conclusions therefore may not be applicable to the role of MTBE in Federal Phase I RFG, which has different characteristics and less stringent emission reductions than CaRFG2.

We have received several comments regarding this conclusion. We summarize the main points brought forth by reviewers and our response to these points below.

While a cost-benefit analysis was performed as part of the overall University of California evaluation, we were not directly involved in that effort and cannot address questions or concerns about the assumptions upon which that analysis was based or the manner in which calculations were performed.

Summary of key criticisms

Several reviewers expressed concern about the statement in the Executive Summary (page 11): "MTBE and other oxygenates were found to have no significant effect on exhaust emissions from advanced technology vehicles. There is no statistically significant difference in the emissions reductions of benzene between oxygenated and non-oxygenated reformulated gasolines that meet all other CaRFG2 standards. Thus, there is no significant additional air quality benefit to the use of oxygenates such as MTBE in RFG relative to non-oxygenated CaRFG2 formulations."

Critiques of this conclusion from various reviewers raise the following main points, which are addressed below:

1. Several reviewers contend that there is insufficient support for this statement because it relies primarily on the Auto/Oil study (Technical Bulletin No. 17, 1995), which is an inadequate basis for formulating a major policy decision. Furthermore, this study does not "directly" compare two fuels that are identical except for MTBE content, and therefore the comparison itself is inconclusive.
2. Several reviewers argue that our conclusion does not sufficiently emphasize the important role played by MTBE and other oxygenates in meeting RFG requirements.
   - MTBE plays an important role in reducing CO emissions.
   - This conclusion ignores the role of CO reductions in decreasing ozone forming potential.
   - MTBE plays an important role as a "diluent" that reduces other undesirable components of gasoline.
3. Several reviewers noted that our statement fails to mention other toxic emissions besides benzene.
4. Reviewers noted that our statement does not contain an adequate definition of "advanced technology vehicles" (referred to as Auto/Oil "jargon"). Reviewers argue that the vehicles tested were prototype vehicles that are not relevant to the real-world, and that such advanced vehicles represent only a small percentage of California's on-road fleet.
5. Reviewers contend that limitations of vehicle dynamometer studies such as the Auto/Oil study should not be extrapolated to real-world, on-road vehicle fleets. Furthermore, such tests predict exhaust emissions only and omit evaporative emissions.
6. Several commenters question the accuracy and basis of the statement that there are "More pronounced emissions benefits in older vehicles."
7. Reviewers contend that oxygenated fuels are a vital way to control automotive CO emissions. Commenters argue that fleet turnover takes a long time, and therefore relying on vehicle technology alone is insufficient to reduce automotive CO.

Several other issues were also raised:

- Oxygenated fuels have other benefits that we did not address, including:

  - reduced particulate matter (PM) emissions, and
  - important emission reduction effects in off-road vehicles and high-emitters.
- Confusion that we extrapolated from our lab results to predict automotive emissions.
- Issue of where in the system products of incomplete combustion (PICs) are formed, and under what conditions (high vs. atmospheric pressure).
- We did not quantify the method detection limits (MDLs) used in our study.

Responses to issues raised

1. *Regarding the cited technical basis for this statement (primarily Auto/Oil, 1995):*

Our cited technical basis for our statement is the Auto/Oil study (Technical Bulletin No. 17, 1995). However, we drew our conclusion based on this study as viewed in totality with other vehicle and on-road studies we reviewed. Thus, our conclusion, as stated in our own portion of the report or in the executive summary, is not based solely on the evidence presented in the Auto/Oil report.

Nevertheless, we do view the evidence of the Auto/Oil study as compelling, and we would like to justify our use of these data and the importance we attach to these results. The Auto/Oil study (1995) is based on comparisons of two CaRFG2 fuels (one with 11 vol% MTBE, the other non-oxygenated) and an industry-average, conventional fuel for a number of different vehicles: 5 passenger cars and one light duty truck in the "Advanced Technology" fleet; seven 1983-1985 MY vehicles; ten 1989 MY vehicles; and six Federal Tier I vehicles (these vehicles meet 1993 California emissions standards and were phased into use in U.S. in 1994-1996 MY).

One important claim made by several reviewers is that the fuels compared in this study are not in fact "comparable" because they are not identical except for MTBE content. For instance, a reviewer from NRDC notes: "If we are to fully understand the benefits of MTBE or other oxygenates for the California fleet, we would need to compare a fleet's emissions when fueled with gasoline containing MTBE as compared with the same fleet using a fuel with otherwise identical characteristics but without MTBE. Both the mass and reactivity of vehicle combustion products and evaporative emissions should be considered in a truly comprehensive analysis."

Unfortunately, in practice it is impossible to create two fuels with identical properties except for MTBE content. The Auto/Oil study compared two different fuel formulations that both met the emissions requirements of the California Predictive Model for CaRFG2. However, the fuels were not identical (see Table A). For instance, in the Auto/Oil study, the two fuels have different octane numbers.

The CaRFG2 with 11 vol% MTBE has an anti-knock index (AKI = (RON + MON)/2) = 92.4, while the non-oxygenated CaRFG2 has an AKI of 90. Thus, the MTBE-fuel has an approximate 2-point octane advantage over the non-oxygenated version. This issue may be more of a cost and marketing issue for refiners than a performance issue, since practically all cars will run on a fuel with an AKI = 87.

Table A. Comparison of fuel properties used in Auto/Oil study (1995, Technical Bulletin No. 17; 1996, 1997).

Fuel parameter	Fuel "A": Conventional gasoline	Fuel "C2": CaRFG2 with MTBE	Fuel "C1": CaRFG2 (non-oxygenated)
Aromatics, vol%	32.0	25.4	22.7
Olefins, vol%	9.2	4.1	4.6
MTBE, vol%	0	11.2	0
Benzene, wt%	1.53	0.93	0.94
Sulfur, ppm	339	31	38
RVP, psi	8.7	6.8	6.9
T10, °F	114	142	142
T50, °F	218	202	208
T90, °F	330	293	297
Net HV, BTU/lb	18,409	18,901	18,596
API gravity	57.4	59.9	62.2
AKI *	87.3	92.4	90

California is the only place in the U.S. where "reformulated gasoline" is not necessarily synonymous with "oxygenated, reformulated gasoline," since Federal RFG must contain 2.0 wt% oxygen by law. Since we were primarily focused on California Phase 2 RFG, we were careful to distinguish between reformulated and oxygenated fuels. There are very few studies that make a direct comparison of vehicle emissions from two different reformulated fuels with and without oxygenates; typically, a reformulated fuel with oxygenate is compared with a conventional fuel, or an oxygenated fuel is compared with a conventional fuel. This paucity of studies is one of the reasons why we cite the 1995 Auto/Oil study. The Auto/Oil database (1996) also directly compares a number of different fuel formulations, including a non-reformulated reference fuel, a CaRFG2 with 11 vol% MTBE, and a non-oxygenated CaRFG2. Hence, while they may have methodological and interpretative limitations, the Auto/Oil studies offer a rare opportunity to observe the disaggregated effects of MTBE and reformulated fuel on vehicle emissions.

2. *Regarding MTBE's contributions to RFG reduced vehicle emissions*.

In our zeal to distinguish the effects of RFG from the effects of MTBE on automotive emissions, we made a conscientious effort to differentiate the two effects. In doing so, we did not explicitly acknowledge the ways in which MTBE does contribute to reductions in vehicle emissions to the extent that several reviewers would have liked.

- *MTBE's impact on reduced CO emissions*.

The presence of MTBE or other oxygenates in fuel reduces automotive exhaust CO emissions by about 2 - 10% per wt% oxygen *depending on vehicle technology* (OSTP, 1997). Thus, a fuel that contains 2.0 wt% oxygen (e.g., 11 vol% MTBE) may reduce exhaust CO emissions by up to 10 - 20%. In fact, as we discuss in our report and summarize in Table 17, there are several dynamometer and on-road studies that have shown CO emission reductions in this range (including Auto/Oil, 1991; Kirchstetter, et al., 1999; Reuter et al., 1992; Hochhauser et al., 1991; Knepper et al., 1993; Mayotte et al., 1994a,b; Most, 1989). However, CO emission reductions are very disparate depending on the vehicle technology. Older vehicles, without catalysts or with open loop operation, benefit the most dramatically from oxygenated fuels; however, in newer vehicles that have closed-loop operation and oxygen sensors, the oxygen in the fuel has virtually no effect on CO emissions.

The effects of oxygenated fuels are uncertain at cold temperatures (e.g., very little testing has been done below 50°F). However, the presence of numerous other confounding factors - most notably, variable meteorological conditions and fleet turnover - make it problematic to correlate ambient CO levels with the use of oxygenated fuels. It appears, however, that CO levels have been decreasing in recent years. Nearly all areas in California meet National Ambient Air Quality Standards for CO.[1]

There persists some degree of confusion about the effects of oxygenates in conventional fuel ("oxyfuels") versus the benefits of reformulated fuel. For instance, a reviewer from the NRDC mentions the study by Kirchstetter et al. (1999) that evaluates on-road emissions, comparing emissions from 1995 (California Phase I RFG, with very little oxygenates) with emissions in 1996 (California Phase 2 RFG, with nearly all gasoline containing 11 vol% MTBE). However, it is misleading and inaccurate to attribute the emissions benefits in 1996 (when CaRFG2 was introduced) – which included substantial reductions in CO, non-methane hydrocarbons, benzene, and 1,3-butadiene – simply to the presence of oxygenate in the fuel, since multiple fuel parameters also changed. Furthermore, effects of vehicle fleet turnover, which are also significant, are embedded in these emission reduction statistics as well.

[1] In 1997, all counties in California except for Los Angeles and Imperial Counties were in compliance with national ambient CO standards. That year, there were four (4) exceedances of the 1 hour (20 ppm) CO standard, all in Calexico. Also in 1997, there were a total of 31 exceedances of the 8 hour (9 ppm) CO standard; these 31 exceedances were distributed over only five monitoring sites.

- *Contribution of CO reductions to ozone forming potential (OFP).*

CO does participate in photochemical reactions leading to the formation of ozone. However, its reactivity in this process as measured by the Carter Maximum Incremental Reactivity (MIR) is only a fraction of that of typical hydrocarbons. Thus, even though CO is emitted from automobile exhaust at levels about 10 times higher than total hydrocarbons, its net contribution to ozone formation is a fraction of that attributed to the hydrocarbons emitted. There is considerable uncertainty about the magnitude of the contribution of CO to total ozone forming potential from automotive emissions; it is perhaps 10-20% of the OFP of emitted hydrocarbons.

Ozone-forming potential *per se* is not incorporated in the California Predictive Model. The model does account for fuel-related emissions reductions in two critical ozone precursors, including total VOCs and NOx, as well as weighted toxic emissions. The impact of CO reductions from oxygenated fuel is not accounted for in determining whether two different fuel formulations meet California Predictive Model emission reduction targets.

The Urban Airshed model is used in Auto/Oil study to project peak ozone concentrations in key urban areas for different fuel formulations. This model incorporates the impact of CO as a reactive species, in the model boundary conditions, and in emissions inventories; thus, CO is included in the model's ozone formation calculations (Auto/Oil, 1994; SAI, 1993). *Therefore, the conclusions of the Auto/Oil study regarding ozone formation of reformulated gasolines include the effect of reductions in CO emissions.* Based on this modeling, the Auto/Oil study concluded that oxygenated CaRFG2 produced "similar but slightly lower predicted peak ozone" compared to non-oxygenated CaRFG2 (Auto/Oil, 1997).

- *MTBE reduces toxic emissions via the "dilution effect."*

The so-called "dilution effect" refers to the fact that MTBE comprises a considerable portion of gasoline in which it is used (typically, 11 vol% in CaRFG2, or up to 15 vol% in wintertime oxyfuels). MTBE is a relatively volatile, clean-burning component of gasoline with a high-octane value. Unfortunately, the terminology used to describe what MTBE "displaces" when it is "added" to fuel creates a misleading impression.

In the case of wintertime "oxyfuels," used in non-reformulated gasoline areas throughout the country, MTBE or another oxygenate is literally "added" to conventional gasoline in a "splash-blending" process. In this case, MTBE does actually "dilute" the conventional gasoline, and the resulting oxyfuel has reduced benzene, aromatics, sulfur, and olefins content compared to conventional gasoline, simply as a result of the addition of MTBE to the base fuel. As a result, oxyfuels produce important, measurable emission reductions compared to conventional gasoline, including decreases in emissions of carbon monoxide, hydrocarbons, benzene and 1,3-butadiene.

However, in the case of reformulated fuels, the presence of oxygenates is an entirely different matter. Because the overall fuel characteristics of RFG are specified, the oxygenate must be "match-blended" with the fuel. That is, the presence of the oxygenate in the fuel alters the whole makeup of the "base fuel" to which it is added, in order to meet overall fuel limits on the vapor pressure, distillation profile, benzene and aromatic content, etc. In California, if refiners use the Predictive Model to ensure compliance of their fuel formulation, they may alter different parameters (as long as they are below the "cap limit") in order to add more or less of a given component. Thus, if refiners choose not to add oxygen to their fuel, they must compensate by altering the profile of their fuel in other ways to achieve net emissions benefits, while still achieving a fuel that has appropriate, desirable characteristics for driving performance.

Thus, in the case of CaRFG2, it is misleading to discuss "taking MTBE out of the gasoline" and "replacing it with x," where x represents some other, presumably undesirable component of gasoline. Refiners must operate within the constraints of the Predictive Model ("cap limits"). For example, gasoline may not contain more than 1.2% benzene; 30% total aromatics, or more than 80 ppm sulfur (Table B). It is undoubtedly a challenging feat for refiners to develop a non-oxygenated reformulated gasoline "recipe" that meets all the predictive model requirements, achieves desirable performance characteristics, and is economically viable. However, as several Bay Area refiners are already demonstrating, doing so is technically feasible.

Table B. California Reformulated Gasoline (CaRFG2) Requirements

Property (maximum)	Flat Limit	Averaging Limit	"Cap" Limit
Reid Vapor Pressure, psi	7.0	---	7.0
Benzene (vol %)	1.00	0.80	1.20
Sulfur (ppmw)	40	30	80
Aromatic hydrocarbons (vol %)	25	22	30
Olefins (vol %)	6.0	4.0	10
Oxygen (wt %)	1.8 – 2.2	---	1.8 (min) ** - 2.7 (max)
T_{50}, °F	210	200	220
T_{90}, °F	300	290	330

** The 1.8 wt% minimum oxygen specification is only in effect during winter months.

Where MTBE is a component of reformulated fuel, it helps achieve the overall benefits of RFG, but we want to emphasize that including MTBE as a component of RFG is not the ONLY means of achieving these reductions. Similar, if not equivalent, emissions benefits may be derived from non-oxygenated RFG formulations.

Thus, we concur with the ARB's comment: "Oxygenates do provide value in that they have blending properties that facilitate meeting the overall specifications for CaRFG2.... We believe it is more accurate to conclude that oxygenates are effective in making gasoline with lower emitting properties but that alternative gasoline formulations that are equally effective and do not use oxygenates are also feasible to produce."

3. Regarding our conclusion's mention of benzene emissions and exclusion of other automotive toxic emissions.

The executive summary of the U.C. report (p. 11) states that there is "no significant difference in benzene emissions" between CaRFG2 with MTBE and the non-oxygenated CaRFG2. In our section of the report (Vol. III), we describe the impacts of MTBE on a much larger number of hydrocarbon species. The explicit mention of benzene in the executive summary and the emphasis on benzene reductions to the exclusion of other toxic emissions should not eclipse our report's discussion of numerous other hydrocarbon species associated with vehicle emissions, from fuels with and without MTBE.

For example, we specifically mention that formaldehyde exhaust emissions increase with the presence of MTBE in gasoline. We state that the only significant difference between the two CaRFG2 fuels is a 13% increase in formaldehyde emissions with the MTBE fuel. The USEPA uses the EPA Complex Model to predict reductions of benzene (7%), acetaldehyde (6%), and 1,3-butadiene (5%) associated with CaRFG2 with 11 vol% MTBE. The agency states, "USEPA does not believe that decreases in other toxic compounds should be ignored on the basis of their statistical significance." The agency believes the projected reductions in benzene, acetaldehyde, and 1,3-butadiene are just as valid as the projected increases in formaldehyde emissions.

Formaldehyde chemistry is quite complex, and secondary formation in the atmosphere from other precursors is indeed an important pathway for ambient formaldehyde formation. A reviewer from SRI has duly noted that one study finds that MTBE fuel actually decreases secondary formaldehyde emissions (citing Spitzer, 1997).

4. Regarding the "inadequate definition" of "advanced technology vehicles."

Several reviewers argue that the vehicles tested in the cited Auto/Oil study (1995) were prototype vehicles that are not relevant to the real-world fleet, since they represent only a small percentage of today's on-road fleet.

The advanced technology vehicles used in the Auto/Oil study were mid-1990s prototypes (at the time), with emissions standards targeted to be lower than (then-current) production standards. In the study, "Advanced Technology" vehicles had 3-way catalysts, exhaust gas recirculation, and sequential or port fuel injection. The vehicles in this fleet consisted of a Chrysler Neon, a Chrysler Voyager, a Ford Escort, a Ford Thunderbird, a GM Cavalier, and a GM LeSabre.

Advanced technology vehicles will represent a growing proportion of the on-road fleet with continuing vehicle turnover and replacement of aging vehicles. According to the California Air Resources Board (ARB, 1998), 1990 – 1995 MY vehicles have emission control systems typical of at least 50% of the on-road fleet in 1996. Vehicles with these emission control systems (three-way catalysts and fuel injection systems) are found in 1986 and newer MY vehicles and accounted for an estimated 70% of the vehicle miles traveled in 1998 (ARB, 1998). Such vehicles contributed an estimated 32% to the total light duty vehicle emission inventory for reactive organic gases, 42% for CO, and 48% for NOx (ARB, 1998).

5. *Regarding contention that limitations of vehicle dynamometer studies such as the Auto/Oil study should not be extrapolated to real-world, on-road vehicle fleets. Furthermore, such tests predict exhaust emissions only and omit evaporative emissions.*

High-emitting vehicles or "gross polluters" are an important issue that must be addressed in order to solve automotive pollution problems. A relatively few number of vehicles contribute a disproportionate amount to overall automotive pollution. However, we do not necessarily advocate designing special fuel formulations as the ideal way to address this particular aspect of automotive pollution; rather, there may be much more effective ways to reduce emissions from these sources.

With respect to the validity of extrapolating from test data to make real-world predictions, we feel that our comprehensive evaluation of a broad spectrum of different types of studies does indeed allow us to make such projections. For instance, the Auto/Oil studies did incorporate evaluation of emissions from older model year vehicles (1983-1985 MY) as well as a limited evaluation of high-emitting vehicles. Furthermore, several of the studies that we reviewed in our report involve on-road emissions testing, which reflects real-world vehicle fleet composition.

While vehicle dynamometer tests do not include evaporative emissions, the Auto/Oil study did evaluate evaporative emissions of different fuel reformulations, and these considerations are reflected in their conclusions.

6. Regarding confusion over the statement that "RFG has more pronounced emission benefits in older vehicles."

The California Air Resources Board (ARB) reviewed our report and expressed concern that the newest class of vehicles showed the greatest percentage reductions of NMOC, NOx, and CO, and the least percentage reductions in the oldest class of vehicles (comparisons of CaRFG2 to reference fuel, Auto/Oil, 1995, Technical Bulletin No. 17). However, because the newest vehicles (in this particular case, Federal Tier I) have absolute emissions that are lower than the older vehicles, comparing percentage reductions is misleading.[2] Absolute reductions are more indicative of the total emissions benefits associated with RFG; and the older vehicles experience much larger emissions benefits from the use of RFG.[3]

Thus, our statement should be amended as follows: "RFG has more pronounced emissions benefits in older vehicles *in terms of absolute emissions benefits*," to avoid this confusion.

7. *Regarding concern that oxygenated fuels are the only viable way to reduce automotive CO emissions*.

Several reviewers expressed concern that because fleet turnover takes a long time, relying on vehicle technology alone is insufficient to reduce automotive CO and to ensure compliance with national ambient air quality standards for CO. However, compliance with national ambient CO standards is no longer an important concern in most parts of California (see response to comment 2 above).

High emitting vehicles are an important concern that must be addressed. Such high emitters include older "gross polluters" without emissions control systems, as well as the emergence of gross polluters caused by the continual aging of fleet and deterioration of emissions control systems even in today's "clean" vehicles. Finally, there are a certain number of malfunctioning gross polluters even within new classes of vehicles.

Nevertheless, given the vast improvements in vehicle emission control technology, fleet turnover does appear to be accomplishing a great deal in terms of overall automotive issues. Of

[2] Absolute emissions (g/mi) of NMHC are 4.5 times higher for 1983-1985 MY vehicles than for Federal Tier I vehicles; NOx emissions are 3.5 times higher, and CO emissions are 3.2 times higher (all comparisons based on CaRFG2 with 11 vol% MTBE) (Auto/Oil, 1995).

course, this trend is undermined as vehicle miles traveled continue to increase, as well as the increasing use of fuel-inefficient SUVs.

Other issues:

- *Regarding other benefits from oxygenated fuels, including*:
  - Reduced particulate matter (PM) emissions, and
  - Important emission reduction effects in off-road vehicles and high-emitters.

Historically, particulate emissions from gasoline automobiles were considered negligible; very little effort has been expended to control them. However, there is growing concern about the possible contribution of high emitters ("smokers") to the formation of primary particulate emissions from gasoline powered vehicles. There is also increasing concern about ultra-fine particulate matter, including the formation of secondary particulates in the atmosphere. Automotive emissions may contribute significantly to the formation of these secondary particulates, particularly from fuels with high aromatic content (Odum, et al., 1997). In this regard, the advent of reformulated fuels, with limited aromatic content, would seem to be advantageous.

The contributions of emissions from off-road gasoline-powered sources to the overall emissions relative to on-road gasoline powered vehicles vary according to pollutant type. For instance, it is estimated that off-road gasoline-powered sources contribute only about 4% of all NOx emissions from gasoline-powered sources (on-road plus off-road), but off-road gasoline sources contribute 21% of CO, 24% of VOC, and 33% of PM_{10} from all gasoline sources (EPA, 1996). As the on-road fleet becomes cleaner with the advance of vehicle technology, off-road sources will become increasingly important. To the extent that off-road sources are largely uncontrolled, reformulated fuel would be predicted to have a beneficial effect primarily in reducing evaporative emissions and emissions of benzene and other toxics. The presence of oxygenates in these sources may be beneficial particularly from a CO emissions perspective.

- *Regarding confusion that we extrapolated from our lab results to predict automotive emissions*

We conducted laboratory studies as one component of our overall research in order to help identify the presence of combustion byproducts associated with the presence of MTBE in CaRFG2. We did not extrapolate from our laboratory studies alone to make predictions about real-world automotive

---

[3] Absolute emissions reductions (g/mi) associated with CaRFG2 compared to conventional gasoline are 64% greater for older vehicles than for Federal Tier I vehicles for NMHC; 70% greater for NOx; and 2.5 times greater for CO (Auto/Oil, 1995).

emissions associated with different fuel types. Our conclusions are based on the relevant collective data, primarily published vehicle dynamometer and on-road studies.

- *Regarding the issue of where in the system PICs are formed, and under what conditions*

Our laboratory study was conducted under atmospheric pressure to simulate the formation of products of incomplete combustion (PICs) in the automotive exhaust manifold. This simulation mimics conditions when unburned fuel escapes from the engine cylinder, as in cold-start emissions or engines running fuel-rich.

Several of the laboratory studies we reviewed were conducted under conditions of high pressure, and would therefore simulate more closely conditions under which fuel is partially burned in the engine chamber.

- *Regarding method detection limits (MDLs) in our study*

Method detection limits for several compounds speciated in our study our summarized below.

Table C. Method detection limits (MDLs) in experimental flow reactor study (Koshland et al., 1998).

Compound	Detection limit, ppm
MTBE	14
Formaldehyde	32
Isobutylene	5
Methanol	12
Tert-butyl formate	1
Benzene	40
Acetaldehyde	38
Acrolein	6
Methacrolein	4

References

Auto / Oil Air Quality Research Improvement Program (1991). Emissions Results of Oxygenated Gasolines and Changes in RVP. *Technical Bulletin No. 6.*

Auto / Oil Air Quality Research Improvement Program (Auto/Oil, 1995). Gasoline reformulation and vehicle technology effects on exhaust emissions. *Technical Bulletin No. 17*.

Auto / Oil Air Quality Research Improvement Program (Auto/Oil, 1996). Phases I and II Test Data Public Release on Compact Disc. Prepared by Systems Application International, Inc. San Rafael, CA. April 5, 1996.

Auto / Oil Air Quality Research Improvement Program (Auto/Oil, 1997). *Program Final Report*.

Auto/Oil (1994). Development of Emissions Reactivity Values for Phase II Results. July 1994. Systems Applications International SYSAPP94-94/053. Page 10.

California Air Resources Board (ARB, 1998). Comparison of the Effects of a Fully-Complying Gasoline Blend and a High RVP Ethanol Gasoline Blend on Exhaust and Evaporative Emissions. *Staff Report*, November 1998, pp 6-7.

EPA, (1997). *National Air Pollutant Emission Trends, 1900-1996.*

Hochhauser, A.M., J.D. Benson, V. Burns, R.A. Gorse, W.J. Koehl, L.J. Painter, B.H. Rippon, R.M. Reuter, J.A. Rutherford (1991). The effect of aromoatics, MTBE, olefins, and T90 on mass exhaust emissions form current and older vehicles – The Auto/Oil Air Quality Improvement Research Program. *SAE Technical Paper Series* No. 912322.

Kenny, Michael R (1999). California Air Resources Board Memorandum to Winston H. Hickox, Secretary for Environmental Protection. Subject: Health & Environmental Assessment of MTBE, November 1998. February 22, 1999.

Kirchstetter, T.W., B.C. Singer, R.A. Harley, G.R. Kendall, J.M. Hesson (1999b). Impact of California Reformulated Gasoline on Motor Vehicle Emissions: 2. Volatile Organic Compound Speciation and Reactivity. *Environ. Sci. Technol.,* **33**(1): xxx.

Kirchstetter, T.W., B.C. Singer, R.A. Harley, G.R. Kendall, M. Traverse (1999a). Impact of California Reformulated Gasoline on Motor Vehicle Emissions: 1. Mass emission rates. *Environ. Sci. Technol.,* **33**(1): xxx.

Knepper, J.C., W.J. Koehl, J.D. Benson, V.R. Burns, R.A. Gorse, Jr., A.M. Hochhauser, W.R. Leppard, L.A. Rapp, R.M. Reuter (1993). Fuel effects in Auto/Oil high emitting vehicles. *SAE Technical Paper Series* No. 930137.

Mayotte, S.C., C.E. Lindhjem, V. Rao, and M.S. Sklar (1994a). Reformulated gasolilne effects on exhaust emissions: Phase I: Initial investigation of oxygenate, volatility, distillation, and sulfur effects. *SAE Technical Paper Series* No. 941973.

Mayotte, S.C., C.E. Lindhjem, V. Rao, and M.S. Sklar (1994b). Reformulated gasolilne effects on exhaust emissions: Phase II: Continued investigation of the effects of fuel oxygen content, oxygenate type, sulfur, olefins, and distillation parameters. *SAE Technical Paper Series* No. 941974.

Most, (1989), *as cited in* Hood, J., and R. Farina (1995). Emissions from light duty vehicles operating on oxygenated fuels at low ambient temperatures: a review of published studies. *SAE Technical Papers Series No*. 952403.

Natural Resources Defense Council (NRDC, 1999). California Hearing on Risks and Benefits of MTBE. Testimony of Janet S. Hathaway, February 23, 1999, before the California Environmental Protection Agency and the California Air Resources Board.

Odum, J.R., T.P.W. Jungkamp, R.J. Griffin, H.J.L. Forstner, R.C. Flagan, and J.H. Seinfeld (1997). Aromatics, Reformulated Gasoline, and Atmospheric Organic Aerosol Formation. Environ. Sci. Technol. 31(7): 1890-1897.

Oxygenated Fuels Association / Systems Application Inc. (1998). A Critical Review of the University of California's Report on Health and Environmental Assessment of MTBE. December 1998.

Reuter, R.M. et al. (1992). Effects of oxygenated fuels and RVP on automotive emissions - Auto / Oil Air Quality Improvement Program. *SAE Technical Paper Series* No. 920326.

SAI (1993). Methodology for Modeling the Air Quality Impacts of Changing the Composition of Fuels used in Light-Duty Gasoline Vehicles. January 1993. Systems Application International, SYSAPP-92/149.

Spitzer, H.L.,(1997). An analysis of the health benefits associated with the use of MTBE reformulated gasoline and oxygenated fuels in reducing atmospheric concentrations of selected volatile organic compounds. *Risk Analysis* 17(6).

SRI Consulting (1999). A Review and Evaluation of the University of California's Report, Health and Environmental Assessment of MTBE. SRIC Project 01101. February 1999.

US EPA, Office of Mobile Sources, Office of Air and Radiation. (1999). SB 521 Research Project Review. February 5, 1999.